NASA TECHNICAL NOTE

NASA TN D-3967

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EVALUATION OF A VERTICAL-SCALE, FIXED-INDEX INSTRUMENT DISPLAY PANEL FOR THE X-15 AIRPLANE

by Lee E. Lytton

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1967

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SUMMARY

A comparative evaluation was performed on an analog simulator to compare pilot performance when using the operational X-15 instrument panel and a panel incorporating vertical-scale, fixed-index flight instruments. The purpose of the evaluation was to provide experimental evidence to complement pilot opinion concerning the acceptability of the vertical-scale panel for use in the X-15 airplane. This evidence was obtained in the form of a wide variety of performance measures for 16 subjects, for two different representative mission profiles, and over three trials or runs for each profile. The data were subjected to both parametric and nonparametric statistical analysis.

Performance differences between panels were largely either insignificant or were masked by variability within subjects. Pilot opinion, as expressed in questionnaires, generally supported this result, in that performance levels for the two panels were judged to be equivalent. Pilot reports, after five X-15 flights, indicate increasing acceptance of the vertical-scale panel as well as operational substantiation of the results of the simulator evaluation.

The need for better indices of performance in displays evaluation seems clear, considering the lack of evident distinction where it is intuitively expected and the fact that the techniques used in this investigation were current.

INTRODUCTION

The vertical-scale instrument display panel now being flight tested in the X-15 airplane represents a major departure from traditional instrument panel design. There is a basic difference in design philosophy between the individual indicators on the vertical-scale panel and those on the standard model, as well as considerable difference in arrangement of the instruments. The panel, which is the result of work carried out under USAF Advance Technology Program 667A (ref. 1), is referred to as the advanced control display subsystem (ACDS) panel.

The design philosophy followed in the ACDS panel established a common reference or "read-line" for the primary flight instruments in order to reduce both the time spent in scanning instruments and the complexity of the scan pattern. A considerable gain in display sensitivity was obtained by using tape scales up to 40 inches long.

Direction of movement of the tape scales was chosen for each parameter to represent most closely the naturally expected result of a particular control action. The ACDS design philosophy is discussed further in reference 1.

Because of the obvious differences between the standard and the ACDS panels and because of evidence of pilot nonacceptance of vertical-scale fixed-index (tape) instruments, an objective evaluation was conducted at the NASA Flight Research Center to determine the suitability of the ACDS panel for flight. The comparison attempted was between two specific, complete panels and not between the concept of vertical-scale and circular-dial instruments. Prior to this study, these display systems had been evaluated almost exclusively in terms of pilot opinion, and the few objective measures taken had concentrated largely on end-point conditions (i. e., merely on peak altitude achieved, for example, versus the planned value).

With the contracted aid of the Life Sciences Group of Douglas Aircraft Company, an experiment was designed that would enable a more objective comparative evaluation to be made of the panels and would provide results that would be significant in a statistical sense. The experimental design recommended by Douglas called for selection of a sizable group of reasonably qualified subjects and the choice of typical appropriate X-15 mission profiles. Required also was a set of dependent variables that would serve both as accurately representative and clearly discriminant measures of performance differences and would lend themselves readily to analysis by statistical techniques. Douglas' participation was based on experience gained during an earlier study (ref. 2) involving auditory flight displays as applied to the X-15, inasmuch as techniques employed therein were directly applicable to the display-panel evaluation.

The purpose of this paper is to describe the design and conduct of the experiment, to report the results of the comparative evaluation, and to point out the need that became apparent for development of better indices of performance in displays evaluation.

SYMBOLS

The units used for the physical quantities in this paper are given in the U. S. Customary Units and, where applicable, in the International System of Units (SI). Factors relating the two systems are presented in reference 3.

g	acceleration due to earth's gravity, 32.2 feet/second^2 (9.8 meters/second^2)
h	inertial altitude, feet (meters)
$\dot{h}$	altitude rate, feet per second (meters per second)
q	dynamic pressure, pounds per foot^2 (newtons per meter^2)
t	time, seconds
V	total velocity, feet per second (meters per second)
α	angle of attack, degrees (radians)

β angle of sideslip, degrees (radians)

γ flight path-angle, degrees (radians)

$\epsilon(t)$ error signal, volts

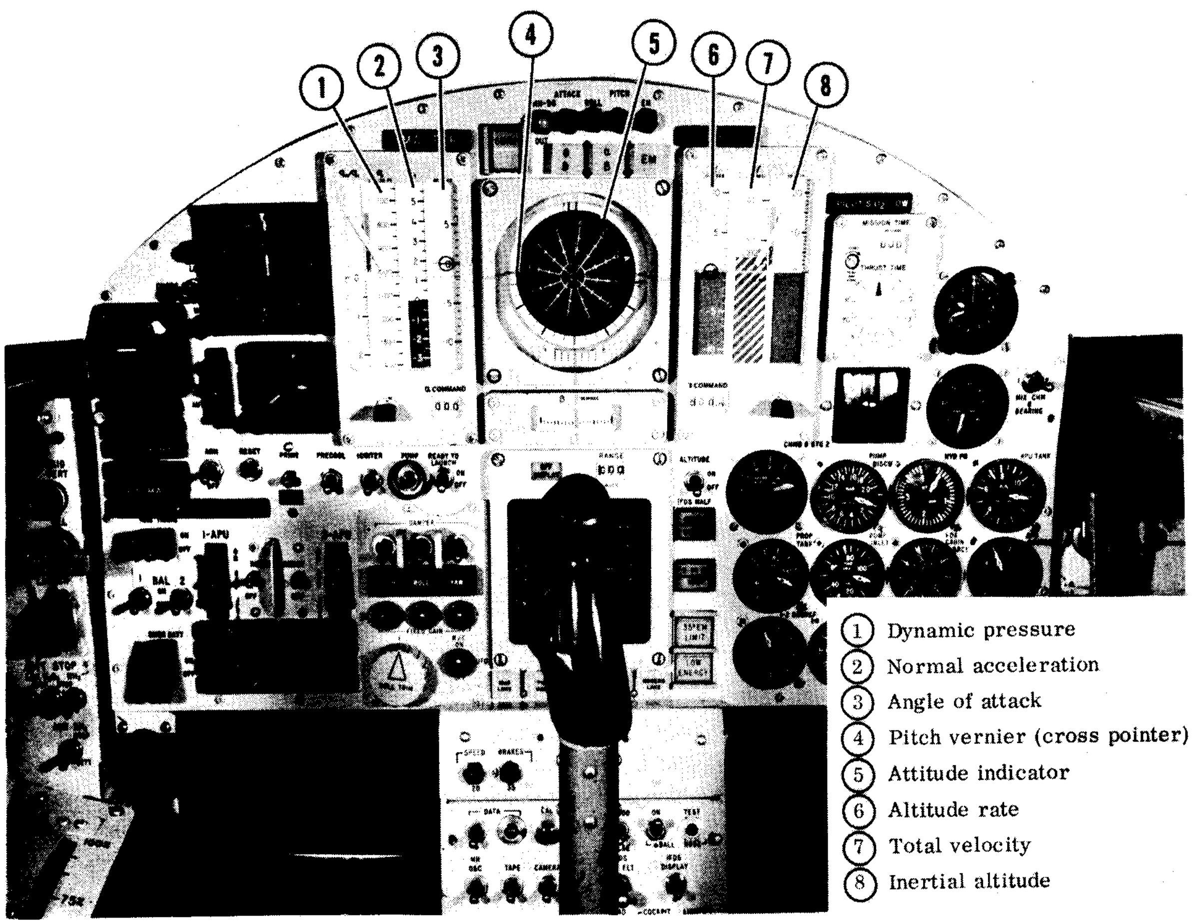
Θ pitch angle, degrees (radians)

φ bank angle, degrees (radians)

Symbols used in appendix C are defined therein.

DESCRIPTION OF THE PANELS

On the ACDS panel (fig. 1) the vertical-scale instruments are grouped so that short-period variables are to the left of the attitude indicator and the more slowly varying parameters are to the right. All the instruments have a common horizontal



E-14907

Figure 1.– ACDS instrument panel.

read-line. On the standard panel (fig. 2) more or less conventional instruments are grouped so that the more important instruments are nearer the attitude indicator. X-15 pilots have become so thoroughly familiar with this layout and the instruments that they are able to garner a great deal of information from pointer rates and positions without having to "read" parametric values.

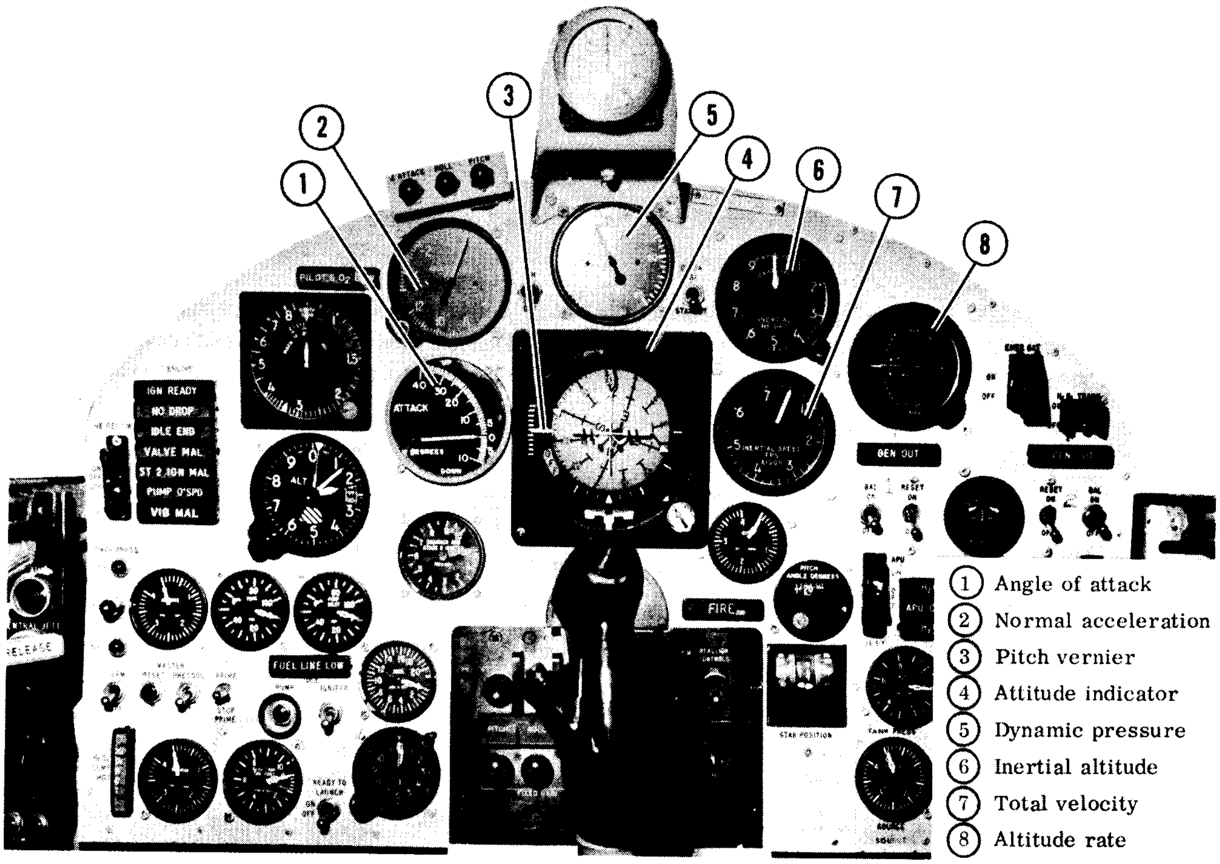


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Figure 2.– Operational instrument panel.

EXPERIMENTAL METHOD

Apparatus used for the experiment included the Flight Research Center's six-degree-of-freedom X-15 analog simulator and one additional computer console, which was programed to provide appropriate functions of error signals for analysis. A detailed description of the X-15 simulator is presented in reference 4.

Sixteen subjects took part in the experiment: six current X-15 pilots, two Flight Research Center research pilots, four X-15 flight planners with considerable simulator experience, two research engineers with military piloting experience, and two engineers with limited private flying experience.

According to the originally proposed experimental design (fig. 3(a)), the 16 subjects were to be divided into eight matched pairs, each member of every pair assigned by coin-toss to one of the panels, and performance of the two resultant groups compared. This was a constrained randomization in that it was desired to have the same number of X-15 pilots, research pilots, engineers, and military pilots in each group. Strictly random assignment might easily have led to the objectionable result of having two of the six X-15 pilots in one group, four in the other, or perhaps even all six in one group. Since each of the 16 subjects actually "flew" both panels to allow subjective comparison, it was possible to collect enough data so that analysis of a second arrangement (fig. 3(b)) could be made as a check. Although this represents a procedural violation in experimental design, the results of this second test are reported since they act as an indication that inequalities in experience and natural ability between groups were relatively minor. The second arrangement can be considered a replication of the experiment, in that the result of the coin-toss which determined each original subject-to-panel assignment could be assumed to be reversed.

Group 1	Group 2		
G_1	G_2	b_1	
G_1	G_2	b_2	B, experience (data runs)
G_1	G_2	b_3	
ACDS a_1	Standard a_2		

A, display

(a) Arrangement 1.

Group 2	Group 1		
G_2	G_1	b_1	
G_2	G_1	b_2	B, experience (data runs)
G_2	G_1	b_3	
ACDS a_1	Standard a_2		

A, display

(b) Arrangement 2.

Figure 3.– Experimental designs.

Mission flight plans were drawn up on the basis of actual flight experience and represented the two main categories of X-15 research missions, the "altitude" flight (mission 1) and the "heating" flight (mission 2). These flight plans, which are reproduced in appendix A, were used in the same way as the standard flight request. Subjects practiced each mission using the flight plan until they had become thoroughly familiar with the various target parameter values and the sequence and timing of cross-checks. The piloting tasks are unique to the X-15 in that parameter ranges are greater and the flight regime varies more drastically than for any other operational aircraft.

For the first mission, immediately after launch at an altitude of approximately 45,000 feet (13,700 meters), the engine was ignited and the throttle advanced to 100-percent thrust. The subject executed a pullup to an angle of attack of 11° (0.19 rad) and held the value for approximately 30 seconds until the aircraft had rotated to a pitch angle of 39° (0.68 rad). A vernier pointer (see figs. 1 and 2) showed null indication at a pitch angle of 39° (0.68 rad), and the piloting task from this point until engine shutdown (at 5150 ft/sec (1570 m/sec) after about 80 seconds at full thrust) consisted of maintaining precise null indication, making correction for thrust misalinements and other disturbances while holding a wings-level ($\varphi = 0°$) (0 rad) attitude. This task involved control over a relatively short-period parameter. After shutdown, the aircraft coasted in a ballistic trajectory to the planned maximum altitude of 250,000 feet (76,200 meters).

The second mission differed in several respects. The subject rotated to a pitch angle of only 20° (0.35 rad) and executed a push-over maneuver to 0g after 42 seconds. At 4700 ft/sec (1430 m/sec) (after about 72 seconds) he reduced throttle setting to minimum thrust then extended the speed brakes to keep from exceeding airplane limits on dynamic pressure. If the subject followed the flight plan closely, he should have arrived at 75,000 feet (22,800 meters) altitude at the end of 74 seconds. His task from this point consisted of maintaining this altitude by steadily increasing angle of attack, meanwhile holding $\varphi = 0°$ (0 rad) until burnout. Control was exercised over this rather slowly varying parameter through the use of g and $\dot{h}$ information, which required considerable skill and experience.

When a subject felt he had achieved a reasonable level of proficiency and the data-processing circuits had been checked out, he made four runs for each mission: three for data, and one a "failure" run. During the failure run, both aircraft generators were failed, which required the subject to reset first the generators then the stability augmentation system (SAS). The position of the failure run in the four-run sequence was varied, and subjects were not told how many runs they would make. Opinions of the subjects were solicited to determine possible comparative effects of such distractions. Each subject was given a copy of a questionnaire immediately after his last data run and asked to complete it as soon as practicable. This questionnaire (see appendix B) provided subjects with an added feeling of participation and made it possible to compare subjective opinions with the results of objective performance measures.

The parameters chosen as dependent variables, six for each mission, are listed in table I.

TABLE I. – DEPENDENT VARIABLES

Mission 1	Mission 2
1. Integral absolute error in φ	1. Integral absolute error in φ
2. Variance of absolute error in φ	2. Variance of absolute error in φ
3. Integral absolute error in Θ	3. Integral absolute error in h
4. Variance of absolute error in Θ	4. Variance of absolute error in h
5. Shutdown velocity error, absolute	5. Velocity error at reduction to minimum thrust, absolute
6. Peak altitude error, absolute	6. Burnout altitude error, absolute

For an error signal $\epsilon(t)$ over an interval of time $t_1 \leqq t \leqq t_2$

$$\text{integral absolute error} = \int_{t_1}^{t_2} |\epsilon(t)| dt$$

and

$$\text{variance of absolute error}^1 = \int_{t_1}^{t_2} \epsilon^2(t)dt - \left(\frac{1}{t_2 - t_1}\right)\left[\int_{t_1}^{t_2} |\epsilon(t)| dt\right]^2$$

These quantities were calculated directly by the computer and recorded as they were generated.

The precision of these measures is difficult to define, largely because of the characteristics of analog computation. Experimental error due to limitations regarding repeatability and accuracy were assumed to be random, so that only systematic differences would be revealed in statistical analysis. The fact that the X-15 simulator has been used successfully for several years in flight planning, pilot training, and handling-qualities investigations testifies to its reliability and accuracy for studies of this type. Only relative sizes of integral error scores were important. Thus, it was necessary only to adjust scaling of error signals experimentally to levels such that overloads in the equipment would not normally occur and "average" performance would result in easily measurable accumulated totals of at least several volts. Values of such parameters as shutdown velocity and altitude and peak altitude were read from digital voltmeters and compared with readings taken by an observer stationed at the cockpit. These recordings were, of course, only as accurate as the simulation itself.

Error scores were transferred from the strip-chart records to data-matrix forms such as that shown in appendix C. From this form the necessary quantities could be readily calculated and used to derive the "F"-ratios which determine whether main and interaction effects are statistically significant. Performance differences were regarded as "consistently significant" when analysis of both arrangements (fig. 3) revealed significant F-ratios. This process is the two-dimensional factorial analysis of variance outlined in appendix C. A more complete discussion of the method is presented in reference 5.

Since several parameters, notably integral absolute error in roll angle, showed such large variations in magnitude from subject to subject, thus weakening the power of the test, a nonparametric or "distribution-free" test was applied as a check. This test procedure is outlined in appendix C and discussed in detail in reference 6.

Finally, performance scores were arranged in a "treatments × subjects" design (fig. 4) so that the scores (averaged over the three trials) of the entire group of 16 subjects could be compared for the two panels, each subject acting as his own

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[1]Variance can aid in discrimination between small continuous errors and large corrected errors, where integral error scores would not. Large integral error-score differences due, for example, to instrument bias (constant error) can thus be recognized, where suspected, by comparison with corresponding variance values.

"control." A "t"-test of the difference in mean scores was made according to the procedure outlined in reference 7, pp. 90-93. Arrangement of the raw data in this form permitted direct examination of differences in each subject's performance on each panel, as well as of differences between experienced subjects and inexperienced subjects.

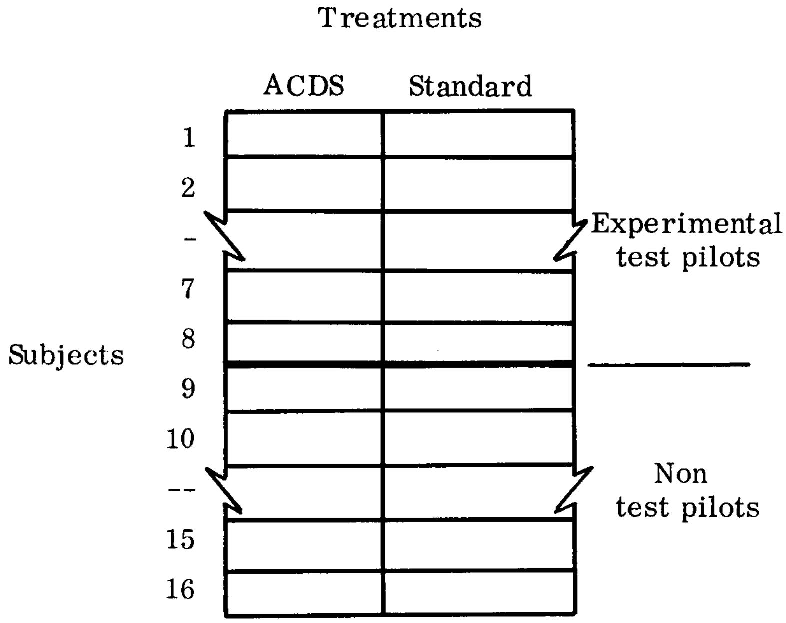


Figure 4.– "Treatments x subjects" design.

The simulator evaluation was followed by operational use of the ACDS panel in the X-15 airplane. After five flights by one of the pilots who had participated in the simulator evaluation, pilot opinion was solicited in order to obtain at least qualitative substantiation of the simulator results.

RESULTS AND DISCUSSION

It was anticipated from the beginning of the evaluation that results obtained would be limited to indications of differences between display panels and consequent suggested directions for further research. Also, it was expected that any differences noted would most likely be few and largely insignificant because of the relative uncertainty of typical measures of human performance.

The following tentative interpretations and conclusions should be reviewed in the light of the limited preannounced goal of determining the suitability of the ACDS panel for flight as compared to the standard panel, the restrictions imposed by subject and equipment scheduling problems, and, above all, the difficulties attached to measuring human performance objectively on other than the most simplified of control-display tasks.

Table II summarizes the results of statistical analysis of the 24 performance measures. An F-ratio greater than 1.44 is regarded as significant at the 0.25 level of confidence. This means that differences as large as those observed would be expected to occur by chance only 25 percent of the time. The choice of the 0.05 and 0.01 levels of confidence in experimental work is frequently only a matter of convention. Under certain conditions the 0.25 level may be more appropriate (in particular, when type 1 errors (rejection of a "true" hypothesis) and type 2 errors (failure to reject a "false" hypothesis) are of equal importance, such as in exploratory work). Variance of integrated error was expected to be of use only as an indicator of the character of the error signal as generated. As such, it is not regarded as a direct performance measure.

TABLE II. - SUMMARY OF F-RATIOS

Mission 1				Mission 2			
Dependent variable	Panels	Trials	Trials × panels	Dependent variable	Panels	Trials	Trials × panels
Arrangement 1							
φ integral	0.45	0.33	0.40	φ integral	0.74	0.86	3.33
φ variance	.23	1.15	.06	φ variance	1.62	.18	3.72
Θ integral	.41	.07	.34	h integral	1.16	.22	1.17
Θ variance	.67	.28	.73	h variance	1.04	1.12	.62
V error	1.94	1.14	.42	V error	[a]3.55	.61	1.90
h error	.53	.25	1.76	h error	[a]2.69	.50	.06
Arrangement 2							
φ integral	0	.02	.70	φ integral	1.02	.50	.98
φ variance	.17	.26	.66	φ variance	2.07	2.40	1.74
Θ integral	.02	2.81	1.75	h integral	1.91	1.44	2.41
Θ variance	1.18	2.88	1.94	h variance	.51	.80	.54
V error	.90	.34	.33	V error	[a]2.58	.13	1.25
h error	2.84	.11	.48	h error	[a]2.28	.99	1.46

[a]F-ratios regarded as "consistently significant."

Significant Differences

Of the direct performance measures taken, only two[1] showed consistent significant differences (i.e., F-ratio greater than 1.44 for both arrangements): absolute error in velocity at reduction to minimum thrust (target V = 4700 ft/sec (1430 m/sec)) and burnout altitude (target h = 75,000 ft (22,800 m)). Both measures were taken on the second mission. In both cases, results favored the ACDS panel. Examination of the altitude and velocity indicators on both panels shows that there is at least one good

[1]Though φ variance is not a direct performance measure, the F-ratios do indicate systematic differences in the way errors were generated, though not in the error scores themselves. This effect should be the subject of further investigation.

reason for these differences. In both instances, the scale resolution of the vertical-scale instruments was effectively doubled over that of the dial-types. The scale was expanded and there were more scale divisions (100 ft/sec per scale division versus 200 ft/sec for the velocity indicator and 1000 feet per scale division versus 2000 feet for the altitude indicator). Whether or not the error score differences are caused by this factor alone is impossible to say, but these particular vertical-scale instruments are demonstrably superior for the particular tasks of reducing thrust at a predetermined velocity and for holding a precise target altitude until burnout.

Primary Control Task

The measures of performance for prime control parameters, pitch-angle integral error for mission 1 and altitude integral error for mission 2, failed to show consistent significant differences (see table II). This can be explained by two factors: (1) pitch-angle deviation from the command value was displayed on both panels by means of a moving pointer on the attitude indicator, and (2) altitude-error measurement was sensitive only to fairly significant deviations, and performance appeared to be more a function of skill and experience than of display. Performance in the attainment of a particular altitude depends greatly on the use of instruments other than the altimeter, in particular, the g meter and rate-of-climb indicator. Despite rather great differences, between panels, in these three instruments, use of the combination apparently had no significant differential effect on performance.

The fact that there are almost no consistently significant F-ratios in either the Trials or Trials × panels columns of table II indicates that subjects' performance did not improve significantly with runs and that performance with regard to runs was not a function of the panel being "flown" (i.e., practice with the ACDS panel had been at least adequate for the comparison).

Secondary Control Task

Since roll angle was not a primary control parameter (the control requirement being merely to maintain $\varphi = 0°$ (0 rad) as nearly as possible during the powered phase), but could be regarded as a secondary or loading task, it was hoped that error score differences due to differences in workload between panels would be detected. Roll error was not expected to be a direct function of display, inasmuch as both panels incorporate the same all-attitude indicator, but differences might suggest that one panel or the other reduced workload on the primary tasks, thus allowing subjects to devote more time to the secondary task. Roll-angle-error integral failed to show significant differences under analysis by a parametric statistical test. But, since score magnitudes varied so greatly among subjects (from less than 0.1 volt to as much as 80 volts), a nonparametric test was applied. Once again, no consistent significant differences were noted. However, since the tests of significance do not allow conclusions to the effect that there are no differences, it can be concluded only that if differences in workload level did exist the experimental measurements were not sensitive enough to detect them.

Choice of Missions

Mission 2 appears to have been a good choice for the program because of the relatively high-level workload it imposed on subjects; mission 1 seems to have been a rather poor choice. This fact was demonstrated by one of the more experienced X-15 pilots who flew this mission easily and successfully using only the three-axis attitude indicator, the angle-of-attack indicator, and the mission timer. A more challenging mission could have been designed especially for the evaluation, but representative, realistic missions seemed to be a more logical choice inasmuch as they would permit comparison with later actual missions.

Treatments × Subjects Analysis

The results of the "treatments × subjects" analysis are summarized in table III in terms of "t"-ratios. A t-ratio of 1.75 indicates significance at the 0.10 level of confidence. On the basis of these results, it would appear that the analysis leads to generally the same conclusions as drawn from the initial analysis, with perhaps greater reliability. Examination of raw scores revealed no apparent trends with respect to differences between experienced and inexperienced subjects.

TABLE III. – SUMMARY OF t-RATIOS

Mission 1		Mission 2	
Dependent variable	t-ratio	Dependent variable	t-ratio
φ integral	0.44	φ integral	1.34
φ variance	.03	φ variance	1.51
Θ integral	.32	h integral	1.59
Θ variance	.89	h variance	1.02
V error	1.39	V error	[a]2.42
h error	[a]3.50	h error	[a]1.96

[a] t-ratios significant at the 0.10 level of confidence.

Questionnaire

Data from questionnaires are so subject to misinterpretation that results can be reported fairly only in the form of summaries of replies to the more relevant queries. Appendix B presents a sample of the original questionnaire along with a tabulation of replies to most questions. Most participants indicated that they judged their own performance to be equivalent for the two panels. This opinion seems to bear out the results of the objective measures.

FLIGHT SUBSTANTIATION

After the evaluation was completed, the ACDS panel was flown successfully five times by the same pilot. Because of the necessarily limited number of flights, results of the evaluation are, of course, preliminary and consist mainly of pilot opinion. There were no significant problems with respect to mechanical operation of the individual instruments.

A questionnaire was given to the pilot who made the flights and comments were requested. The results are shown in appendix D. The pilot reported that his confidence in the ACDS panel increased with simulator practice and flight experience. After four flights, he began to prefer the tape instruments because they reduced cross-check time during the boost phase and generally provided greater resolution than the round-dial instruments. He reported, however, that he missed the "peripheral" information available from pointer rates and positions.

CONCLUSIONS

A comparative evaluation of the vertical-scale fixed-index (ACDS) instrument display panel and the "standard" X-15 panel resulted in the following conclusions:

1. Missions can be carried out as accurately and successfully with the ACDS panel as with the "standard" model. Further training with the ACDS panel might, however, result in clearer distinctions in performance level.

2. In determining particular target values, such as a definite shutdown velocity or a given altitude, the greater resolution of the vertical-scale instruments most likely resulted in significantly improved performance.

3. For the most part, the dependent variables selected as performance measures proved to be either too sensitive to intersubject variability or not sufficiently direct functions of display to allow conclusions to be drawn about overall performance.

4. Pilot opinion, as expressed in questionnaires, tends to support the objective results of the evaluation insofar as most subjects felt their performance and workload levels to be nearly equivalent for the two panels.

Five flights of the ACDS panel in the X-15 airplane resulted in a limited operational substantiation of these conclusions on the basis of comments by the pilot.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., January 11, 1967
125-19-02-02-24

APPENDIX A

ACDS PANEL EVALUATION FLIGHT PLANS

FLIGHT PLAN NO. 1 – ALTITUDE

Item	t, sec	h, ft $\times 10^3$	V, ft/sec	α, deg	q, lb/ft^2	Event
1.	0	45	790	2	145	Launch, light engine, increase to 100 percent thrust. Rotate to $\alpha \approx 11^\circ$, maintain $\alpha \approx 11^\circ$ to $\Theta = 39^\circ$.
2.	30	54	1800	11	550	$\Theta = 39^\circ$, maintain $\Theta = 39^\circ$.
3.	82	139	5150	7	50	Shut down at 5150 ft/sec, push over to $\alpha \approx 0^\circ$. Engine Master "OFF", RAS* "ON", pitch SAS hi.
4.	170	250	4300	0	.8	Peak altitude, extend speed brakes to 20°.
5.	175	---	----	--	---	End of run.

Special Instructions

1. Use SAS
   - Pitch off until burnout
   - Roll - lo
   - Yaw - hi
2. RAS off until burnout
3. For ACDS panel, push Θ, β switch, and set $\alpha_{command} = 11^\circ$.
4. When generator failure occurs,
   a) reset both generators
   b) reset all SAS channels by switching to off, then to the proper gain.

FLIGHT PLAN NO. 2 – HEATING

Item	t, sec	h, ft $\times 10^3$	V, ft/sec	α, deg	q, lb/ft^2	Event
1.	0	45	790	2	145	Launch, light engine, increase to 100 percent thrust. Rotate to 10° α until $\Theta = 20^\circ$.
2.	18	47	1500	10	450	$\Theta = 20^\circ$, maintain $\Theta = 20^\circ$.
3.	42	59	2700	4	870	Push over to 0 g.
4.	72	75	4700	0	1200	Reduce to minimum thrust.
5.	74	75	4800	0	1250	Modulate speed brakes ($\approx 35^\circ$) to maintain slow longitudinal acceleration, increase α to maintain h = 75,000 feet.
6.	90	75	5020	3	1400	Burnout. Retract speed brakes, maintain h = 75,000 feet.
7.	---	--	----	--	----	$\dot{h} = 0$, maintain $\dot{h} = 0$.
8.	125	--	----	--	----	End of run.

Special Instructions

1. Use SAS
   - Pitch - hi
   - Roll - lo
   - Yaw - hi
2. RAS off
3. For ACDS panel, push Θ, β switch, and set $\alpha_{command} = 10^\circ$, $\gamma = 0^\circ$.
4. When generator failure occurs,
   a) reset both generators
   b) reset all SAS channels by switching to off, then to the proper gain.

* Reaction augmentation system

APPENDIX B

SUMMARY OF REPLIES FROM 12 OF 16 SUBJECTS

QUESTIONNAIRE - ACDS Panel Evaluation

Key (items 5, 9, 16)

- Research pilots
- Engineers
- Flight planners

NAME: ______________________________

DATE: ______________________________

For questions requiring a rating, place an "X" on the scale provided. Please feel free to add any comments you may want to make relative to any of the questions.

1. Approximately how much instrument flight experience have you had ?

   From 0 to nearly 1200 hours simulated and actual flight time. Average, 400 hours.

2. What previous experience, if any, have you had with vertical-scale instruments of the type used in the ACDS panel ?

   2 - took part in earlier evaluation
   3 - took part in single-instrument evaluation or F-106 panel flight tests
   1 - took part in energy-management work using ACDS
   5 - no previous experience
   1 - did flight-planning work with ACDS panel

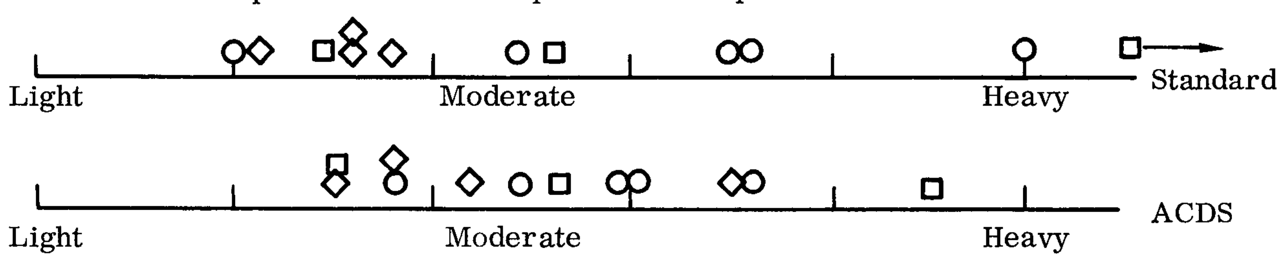
3. Do you believe that vertical-scale fixed-reference (tape) displays have definite value in the X-15 mission ?

   7 - yes
   4 - no
   1 - "yes and no"

4. Indicate your feeling about the suitability of the two missions for comparison and evaluation of the panels.

   6 - O.K. to good
   5 - O.K. with qualifications
   1 - no response

5. How did pilot workload compare between panels ?



6. Did you feel as if you were forced to concentrate harder to pick out definite values of parameters (for example, in accomplishing shutdown at a definite velocity) for the ACDS panel ?

4 - yes
5 - no
2 - yes, slightly
1 - "yes and no"

7. How did you feel about the naturalness and interpretability of vertical-scale instruments as compared to standard ones (for example, in regard to direction and rate of tape movement, scaling, and sensitivity) ?

More difficult — Easier — Vertical scale

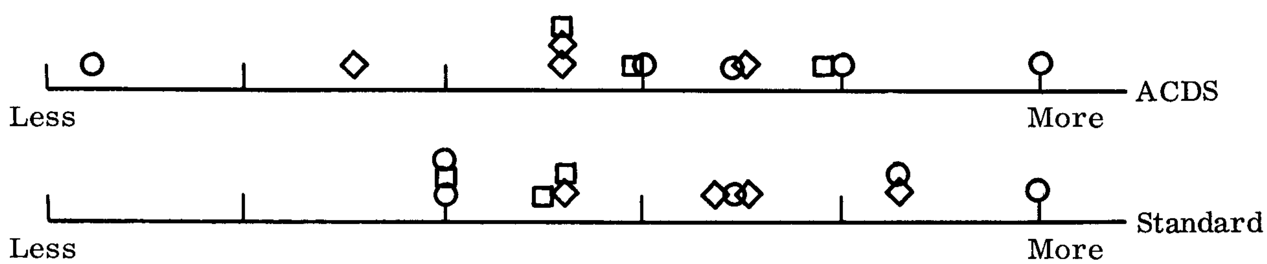
More difficult — Easier — Standard

This scale largely misinterpreted; replies difficult to summarize.

8. Do you think further training with the ACDS panel would improve your performance significantly ?

7 - yes
5 - no

9. How do you rate the overall suitability of the panels for the X-15 mission ?



10. Does the fact that parameter values must be read on the ACDS panel bother you? That is, do you notice loss of cues you may be used to picking up from judgment of needle or pointer position and rates ?

11 - yes
0 - no
1 - "yes and no" (depends on parameter)

11. Do you think some sort of "hybrid" display panel, combining the best features of both ACDS and standard panels should be designed ?

5 - yes (qualified)
1 - no, stay with fixed scale, moving pointer
2 - worth investigating

2 - have to try it to judge
1 - no response
1 - think better design possible

12. Do you prefer having α (angle of attack) displayed on a moving-pointer or on a moving-tape display? What about velocity and altitude--does a circular scale seem more legible, or do you prefer it because you are used to it?

1 - no response
5 - prefer moving pointer, circular or linear scale
5 - prefer tape
1 - "mixed feelings"

13. Immediately after emergency conditions, did you experience any difficulty or confusion upon returning your attention to either panel?

5 - yes
- 1 - ACDS better
- 2 - standard better
- 2 - no difference noted

7 - no

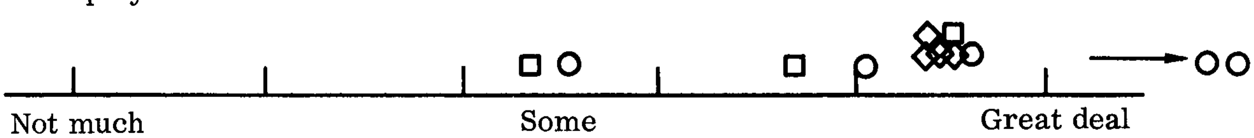
14. What parameters do you think would best be used to measure pilot performance in evaluation of displays?

Opinions vary widely; difficult to summarize.

15. Do you think simulator results will be valid or do you think valid panel evaluation can be made only in flight? That is, do you think the simulation has been tested and proved to the point that results of this type of evaluation can be trusted?

2 - yes
2 - no
8 - valid, subject to confirmation by flight test

16. How much emphasis do you think should be placed on pilot judgment or opinion in displays evaluation?



APPENDIX C

STATISTICAL METHODS

FACTORIAL ANALYSIS

The model for the two-dimensional factorial analysis of variance with repeated measures on one factor (see ref. 5) is shown below:

a_1	a_2	
G_1	G_2	b_1
G_1	G_2	b_2 B (experience)
G_1	G_2	b_3
ACDS	Standard	

A (display)

in which A represents the between-subject variable with levels a_i, $i = 1, 2, \ldots p$ (here, panels a_1, a_2), B represents the within-subject variable with levels b_j, $j = 1, 2, \ldots q$ (here, trials b_1, b_2, and b_3).

Subjects are denoted by the subscript $l = 1, 2, \ldots n$ ($n = 8$), and X_{ijl} denotes the score for subject l in all i j of the data matrix. A sample data matrix form is shown below:

Mission Profile No. __________ Dep. Var. ______________

Display	Subject	Trial 1	Trial 2	Trial 3	Total
	1	X_{111}	X_{121}	X_{131}	
	2	----	----	----	
	3	----	----	----	
Standard	4	----	----	----	
	5	----	----	----	
	6	----	----	----	
	7	----	----	----	
	8	X_{118}	X_{128}	X_{138}	
	Total				
	9	X_{211}	X_{221}	X_{231}	
	10	----	----	----	
	11	----	----	----	
ACDS	12	----	----	----	
	13	----	----	----	
	14	----	----	----	
	15	----	----	----	
	16	X_{218}	X_{228}	X_{238}	
	Total				
	Total				

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It is assumed that both groups (each G assigned to one panel) are random samples from the same population and that distribution of scores for each treatment condition population is normal and has the same variance. The null hypothesis that mean scores for each treatment condition population are equal is tested to determine the following:

1. Differences due to any one variable (e.g., panels) across all levels of the remaining variable (trials).

2. Differences due to combinations of two (or three) variables across all levels of the remaining variable but not due to effects of the type described in item 1 (interactive effects).

The hypothesis is tested by means of the F-test. A confidence level of 0.25, a commonly used value for experiments with few subjects and trials, was chosen for these tests.

To determine the proper ratios for the F-test, the total sum of squares of deviation of the variables X_{ijl} from their sample mean $\overline{\overline{X}}$ is first broken down into components as follows:

$$\sum\sum\sum\left(X_{ijl} - \overline{\overline{X}}\right)^2 = \underbrace{\sum\sum\sum\left(\overline{X}_{i..} - \overline{\overline{X}}\right)^2 + \sum\sum\sum\left(\overline{X}_{i.l} - \overline{X}_{i..}\right)^2}_{\text{between-subject variance}}$$

$$\underbrace{+\sum\sum\sum\left(\overline{X}_{.j.} - \overline{\overline{X}}\right)^2 + \sum\sum\sum\left(\overline{X}_{ij.} - \overline{X}_{i..} - \overline{X}_{.j.} + \overline{\overline{X}}\right)^2 + \sum\sum\sum\left(X_{ijl} - \overline{X}_{ij.} - \overline{X}_{i.l} + \overline{X}_{i..}\right)^2}_{\text{within-subject variance}}$$

where subscripted dots indicate summation over replaced indices, for example, $X_{i..} = \sum_{j}\sum_{l} X_{ijl}$. Then it is merely necessary to divide each sum of squares by its degrees of freedom and form the proper ratio depending on the hypothesis to be tested. For example, in testing for differences due to panels, the first and second terms would form an F-ratio. If the computed value of this F should exceed the expected value of F in the appropriate distribution (determined by $df_{numerator}$, $df_{denominator}$) for the chosen confidence level, the null hypothesis may be rejected.

COMPUTATIONAL PROCEDURES

To simplify the computations required in these tests, the following quantities are calculated first:

(1) $$\frac{\left(\sum_{l=1}^{n}\sum_{j=1}^{q}\sum_{i=1}^{p} X_{ijl}\right)^2}{npq}$$

(2) $$\sum_{l=1}^{n}\sum_{j=1}^{q}\sum_{i=1}^{p} X_{ijl}^2$$

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$$(3)\quad \frac{\sum_{i=1}^{p}\left(\sum_{l=1}^{n}\sum_{j=1}^{q} X_{ijl}\right)^2}{nq} \qquad (4)\quad \frac{\sum_{j=1}^{q}\left(\sum_{l=1}^{n}\sum_{i=1}^{p} X_{ijl}\right)^2}{np}$$

$$(5)\quad \frac{\sum_{j=1}^{q}\sum_{i=1}^{p}\left(\sum_{l=1}^{n} X_{ijl}\right)^2}{n} \qquad (6)\quad \frac{\sum_{l=1}^{n}\sum_{i=1}^{p}\left(\sum_{j=1}^{q} X_{ijl}\right)^2}{q}$$

Then, the following quantities are calculated:

$SS_{BET} = (6) - (1)$

$SS_A = (3) - (1)$

$SS_{error(b)} = (6) - (3)$

$SS_{WITH} = (2) - (6)$

$SS_B = (4) - (1)$

$SS_{AB} = (5) - (3) - (4) + (1)$

$SS_{error(w)} = (2) - (5) - (6) + (3)$

$df_{bet} = n.p - 1$

$df_A = p - 1$

$df_{error(b)} = p(n - 1)$

$df_{WITH} = np(q - 1)$

$df_B = q - 1$

$df_{AB} = (p - 1)(q - 1)$

$df_{error(w)} = p(n - 1)(q - 1)$

$$MS_A = \frac{SS_A}{df_A}$$

$$MS_{error(b)} = \frac{SS_{error(b)}}{df_{error(b)}}$$

$$MS_B = \frac{SS_B}{df_B}$$

$$MS_{AB} = \frac{SS_{AB}}{df_{AB}}$$

$$MS_{error(w)} = \frac{SS_{error(w)}}{df_{error(w)}}$$

Differences in the measure X_{ijl} attributed to each variable (A, B) and to interaction (A × B) are tested as follows:

1. Determine the desired level of confidence α. In this case, $\alpha = 0.25$.

2. If the value of F from the following table exceeds the value of F in the appropriate distribution (determined by $df_{numerator}$, $df_{denominator}$) for the chosen value of α, the null hypothesis that "There is no difference in X_{ijl} attributable to this source" is rejected (i.e., if the null hypothesis is true, the difference is so large that it would occur by chance less than the fraction α of the time).

Source	F	$df_{numerator}$	$df_{denominator}$
A	$\frac{MS_A}{MS_{error(b)}}$	df_A	$df_{error(b)}$
B	$\frac{MS_B}{MS_{error(w)}}$	df_B	$df_{error(w)}$
A × B	$\frac{MS_{AB}}{MS_{error(w)}}$	df_{AB}	$df_{error(w)}$

APPENDIX C

DISTRIBUTION-FREE TEST

Since several of the dependent variables appeared to violate the assumptions underlying the parametric analysis of variance, a distribution-free or nonparametric test was used (see ref. 6). This test is based on the χ^2 distribution, with the following notation:

X_{ijl} = score for subject l, cell ij of the data matrix, as in the preceding analysis of variance design

n_{ij} = number of scores in cell ij (in this case, all $n_{ij} = n$)

$$n_{i.} = \sum_{j=1}^{q} n_{ij}, \quad n_{.j} = \sum_{i=1}^{p} n_{ij}, \quad N = \sum_{j=1}^{q} \sum_{i=1}^{p} n_{ij}$$

Find Md = median of the entire set X_{ijl} of scores. If there is no such number, let Md be the number which most nearly divides the set X_{ijl} into two equal sets of numbers.

Let

$$af_{ij} = \text{number of } X_{ijl} > Md$$

$$bf_{ij} = \text{number of } X_{ijl} < Md$$

$$N_a = \text{total number of } X_{ijl} > Md$$

$$N_b = \text{total number of } X_{ijl} < Md$$

$$af_{i.} = \sum_{j=1}^{q} af_{ij}, \quad bf_{i.} = \sum_{j=1}^{q} bf_{ij}$$

$$af_{.j} = \sum_{i=1}^{p} af_{ij}, \quad bf_{.j} = \sum_{i=1}^{p} bf_{ij}$$

Then calculate

$$\chi_T^2 = \sum_{j=1}^{q} \sum_{i=1}^{p} \left\{ \frac{af_{ij} - n_{ij}\frac{N_a}{N}}{n_{ij}\cdot\frac{N_a}{N}} + \frac{\left(bf_{ij} - n_{ij}\frac{N_b}{N}\right)^2}{n_{ij}\cdot\frac{N_b}{N}} \right\}$$

$$\chi_A^{\,2} = \sum_{i=1}^{p} \left\{ \frac{\left(af_{i.} - n_{i.}\frac{N_a}{N}\right)^2}{n_{i..}\frac{N_a}{N}} + \frac{\left(bf_{i.} - n_{i.}\frac{N_b}{N}\right)^2}{n_{.j.}\frac{N_b}{N}} \right\}$$

$$\chi_B^{\,2} = \sum_{j=1}^{q} \left\{ \frac{\left(af_{.j} - n_{.j}\frac{N_a}{N}\right)^2}{n_{.j.}\frac{N_a}{N}} + \frac{\left(bf_{.j} - n_{.j}\frac{N_b}{N}\right)^2}{n_{.j.}\frac{N_b}{N}} \right\}$$

Main and interaction effects are tested as follows:

1. Select a level of significance α (0.25).

2. Reject the hypothesis that a variable has no effect on the measure X_{ijl}, at α level of significance, if the calculated χ^2 exceeds the χ^2 table value for the chosen α and appropriate degrees of freedom (df) as indicated in the following table:

Variable	χ^2	df
A	$\chi_A^{\,2}$	p - 1
B	$\chi_B^{\,2}$	q - 1
A × B	$\chi_I^{\,2} = \chi_T^{\,2} - \chi_A^{\,2} - \chi_B^{\,2}$	(p - 1) (q - 1)

APPENDIX D

RESULTS OF FLIGHT EVALUATION

QUESTIONNAIRE - ACDS Panel Flight Evaluation

NAME: ______________________________

DATE: ______________________________

1. Approximately how many hours have you spent in flight preparation with the ACDS panel ?

150 hours

2. Has your confidence in the ACDS panel increased with experience (since the simulator evaluation) ?

Yes. For the first 70 to 80 hours on the simulator and the first two flights I would have preferred round instruments. By the third flight I was neutral, and after the fourth flight I preferred the tapes (with reservations).

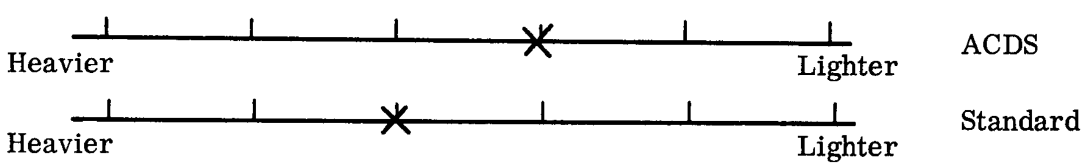
3. Have you noticed any gross difference between simulator and airplane confidence level (with the addition of motion cues as well as the need to monitor engine, subsystem instruments) ?

Confidence level is the same. There is a definite reduction in cross-check during the flight. This is due to tighter check of the primary parameters (e.g., θ) leaving less time for checking lesser parameters.

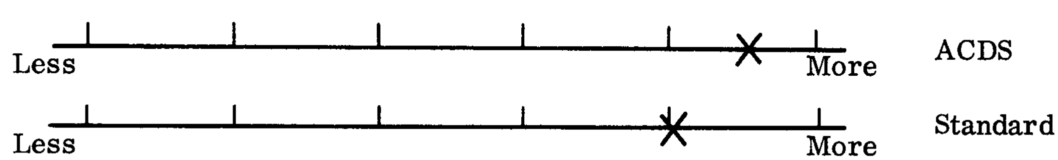
4. Do you believe, after flight experience, that vertical scale, fixed-reference displays have definite value in the X-15 mission?

Yes. They unburden the pilot during boost by reducing cross-check time. Generally, they also provide better resolution (e.g., vertical speed).

5. How does pilot workload compare (in flight) between panels ?



6. How do you rate the overall suitability of the two panels for flight ?



7. Do you think the simulator evaluation was valid, after flight experience ? Results of the simulator effort indicated little measurable difference in performance between panels.

Yes. Sounds like a valid evaluation.

8. Did you experience any instances of momentary confusion or disorientation (other than that due to mechanical difficulties) ?

Not in flight. I have experienced some confusion in the sign of angle-of-attack rate during pitch-damper-off work in the simulator.

9. How has in-flight performance been in regard to planned versus achieved peak altitude, shutdown velocity, etc. ?

No profile errors have resulted from erroneous tape information. There does appear to be a slight lag of the velocity tape in flight.

10a. What features, if any, of the ACDS panel do you like ?

Resolution of all tapes, range of $\dot{h}$ tape.

10b. What features do you find objectionable, if any ?

Can misinterpret direction of angle-of-attack rate of change. Peripheral information is not as good as on round dials. Normal accelerometer is not as reliable as mechanical one.

REFERENCES

1. Anon.: Control-Display Subsystem for Manned Advance Aeronautical and Aerospace Vehicles. Eng. Rep. GR-1429, Lear Siegler, Inc., Sept. 1963.

2. Katz, Darryl; Emery, Jerry A.; Gabriel, Richard F.; and Burrows, Alan A.: Experimental Study of Acoustic Displays of Flight Parameters in a Simulated Aerospace Vehicle. NASA CR-509, 1966.

3. Mechtly, E. A.: The International System of Units - Physical Constants and Conversion Factors. NASA SP-7012, 1964.

4. Cooper, Norman R.: X-15 Flight Simulation Program. IAS Paper No. 61-194-1888. June 13-16, 1961.

5. Winer, B. J.: Statistical Principles in Experimental Design. McGraw-Hill, 1962.

6. Wilson, Kellogg V.: A Distribution-Free Test of Analysis of Variance Hypotheses. Psychological Bull., vol. 53, no. 1, 1956, pp. 96-101.

7. Lindquist, E. F.: Design and Analysis of Experiments in Psychology and Education. Houghton Mifflin Co. (Boston), 1956.

NASA-Langley, 1967 —— 2 H-446